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Tests of Space Vehicles

by

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Structural Tests of Satellites

- Course Outline
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  - 2.0 Structural Environments
  - 3.0 Definitions
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Structural Tests of Satellites

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  - 5.4 Random
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  - 5.7 Shock
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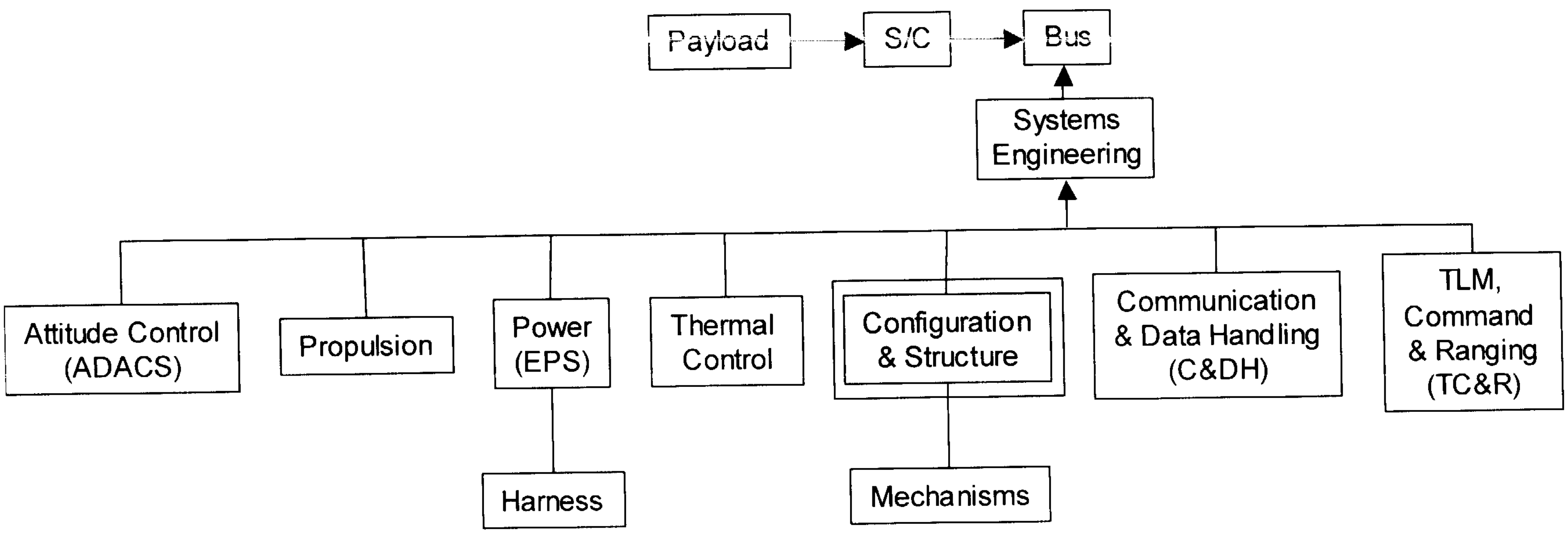
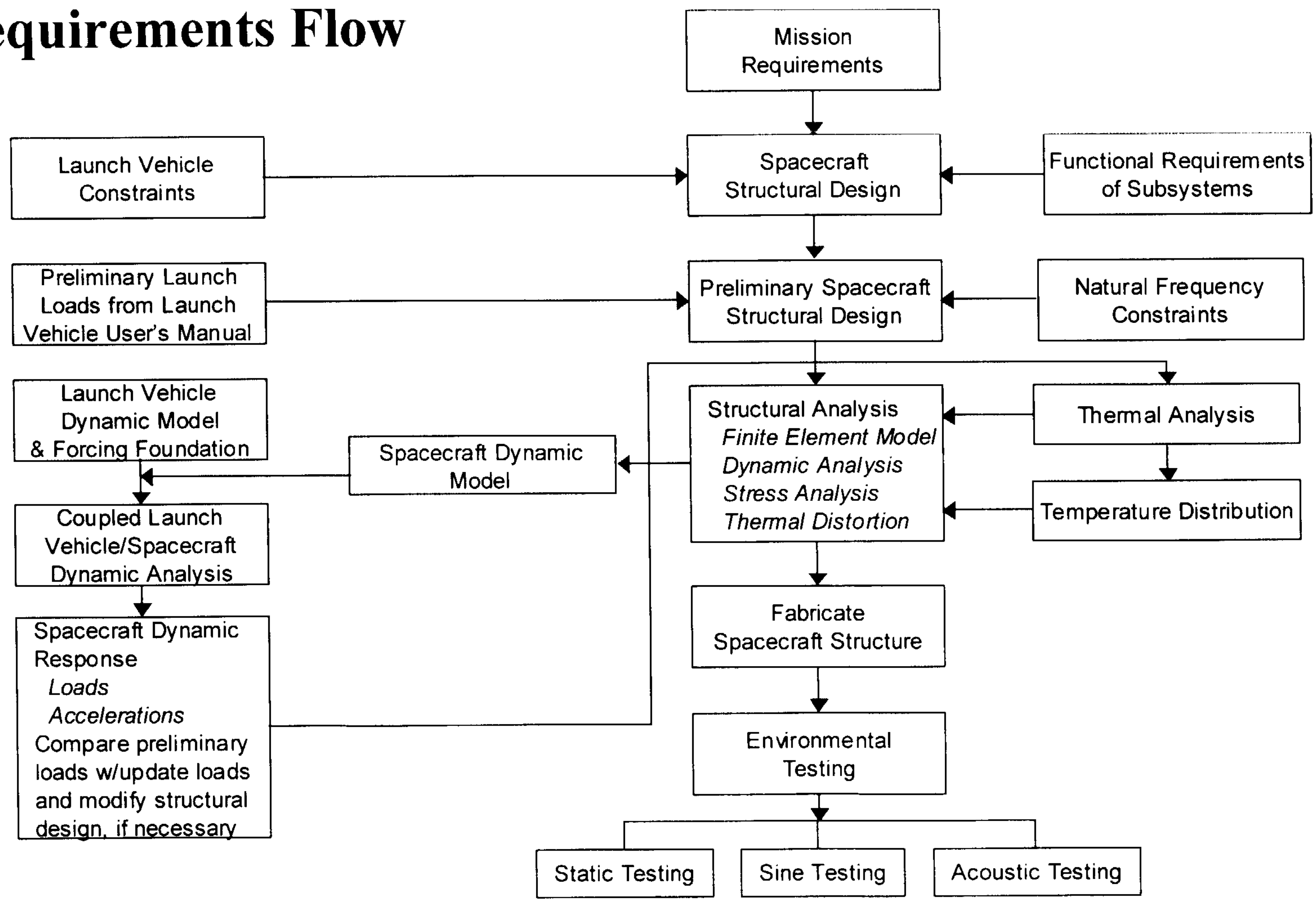
Structural Requirements



Structural Requirements

Requirements Flow



Structural Environments

- The FS table is to be used with a set of maximum flight expected environments (MEE) or also called limit load requirements.
- Typical loads:

Type of Excitation	Environment	Main Design Impact
Steady state acceleration	Boost phases quasi static accelerations	Primary structure
Low frequency transient	Engine ignition overpressure, liftoff release, thrust transients, engine cut off, engine shut down	Secondary structure
Interior acoustic noise	Engine noise, buffeting, boundary layer noise	Equipment / structure
Random structureborne vibration	Engine generated vibration	Equipment / structure
High frequency transients	Pyrotechnic events such as interstage separation, fairing jettisoning	Shock sensitive equipment

Structural Environments

TYPES OF DYNAMIC ENVIRONMENTS

Dynamic environments include all phenomena that produce fluctuating excitations (also called forcing functions or dynamic loads) that act on a spacecraft and/or its constituent components. The excitations may occur physically as either an applied force or an input motion, and may be either internally or externally induced.

To facilitate data analysis and testing procedures, dynamic environments are commonly classified as being deterministic, random, or a mixture of both. They also are usually classified as being stationary, nonstationary, or transient in character.

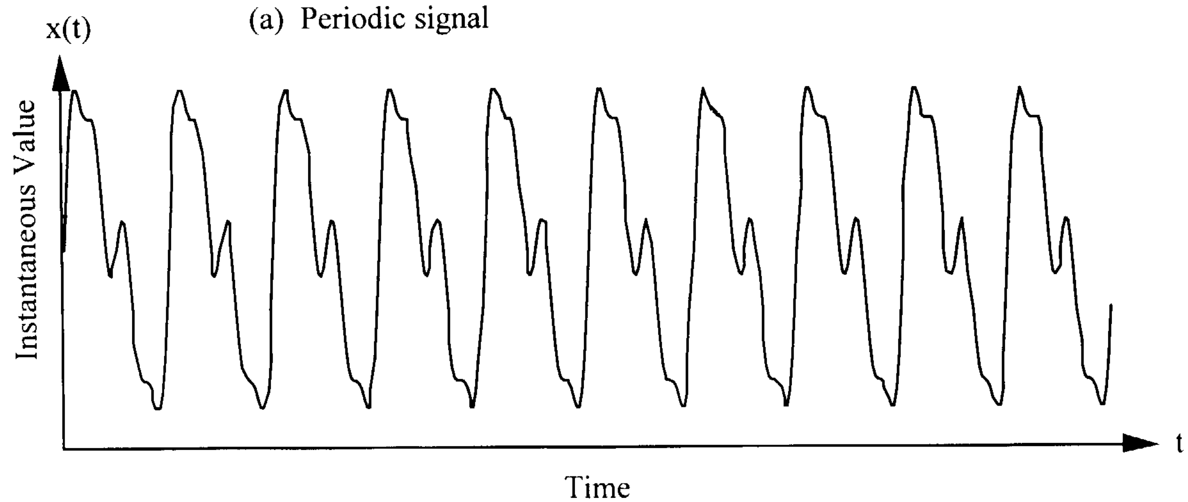
Another type of environments clasification are stationary, nonstationary, or transient in character.

Structural Environments

DETERMINISTIC ENVIRONMENTS

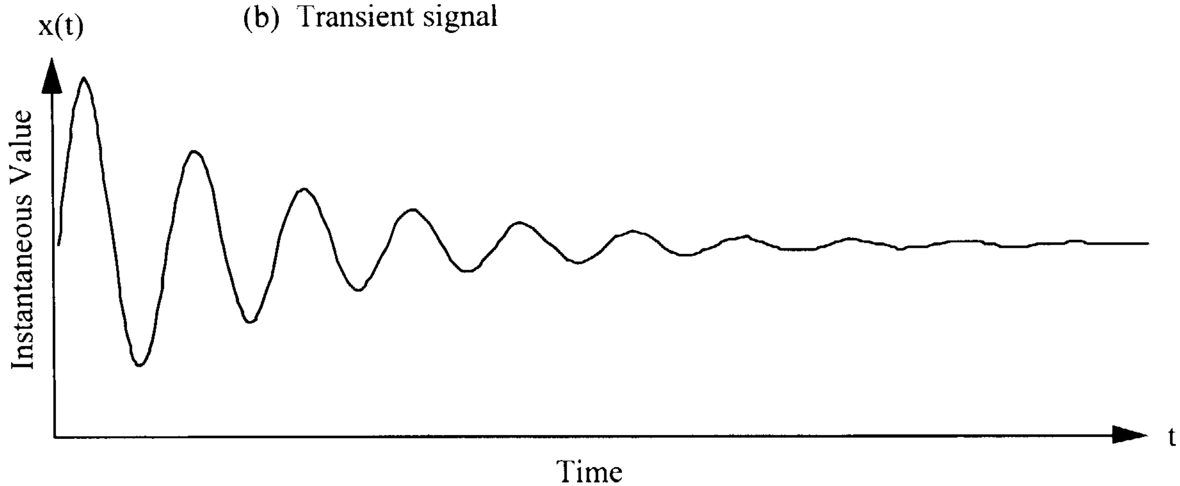
A deterministic dynamic environment is one that produces an excitation with the same time history each time the environment occurs

(a) Periodic signal



Structural Environments

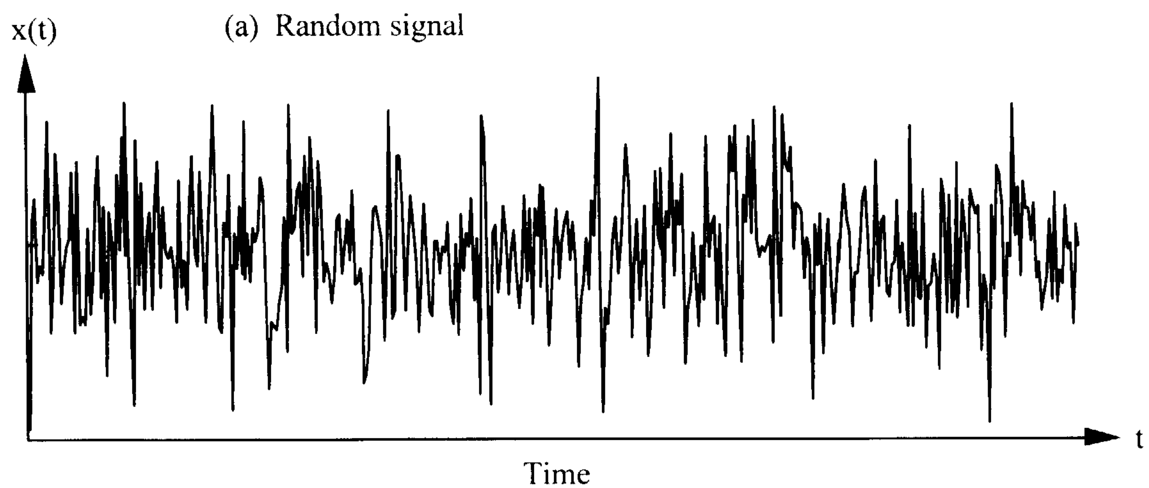
(b) Transient signal



Structural Environments

RANDOM ENVIRONMENT

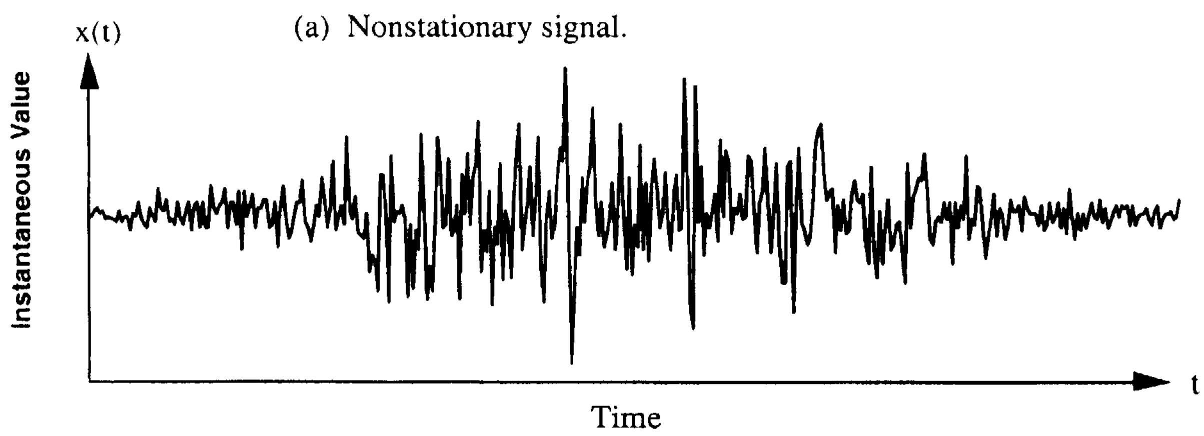
- The average property of the time history signal (mean and standard deviation) might be the same each time the environment occurs, but the exact time history signal is not the same and, hence, the exact value of the signal at a specific time t cannot be predicted in advance based on a previous measurement.



Structural Environments

STATIONARY, NONSTATIONARY

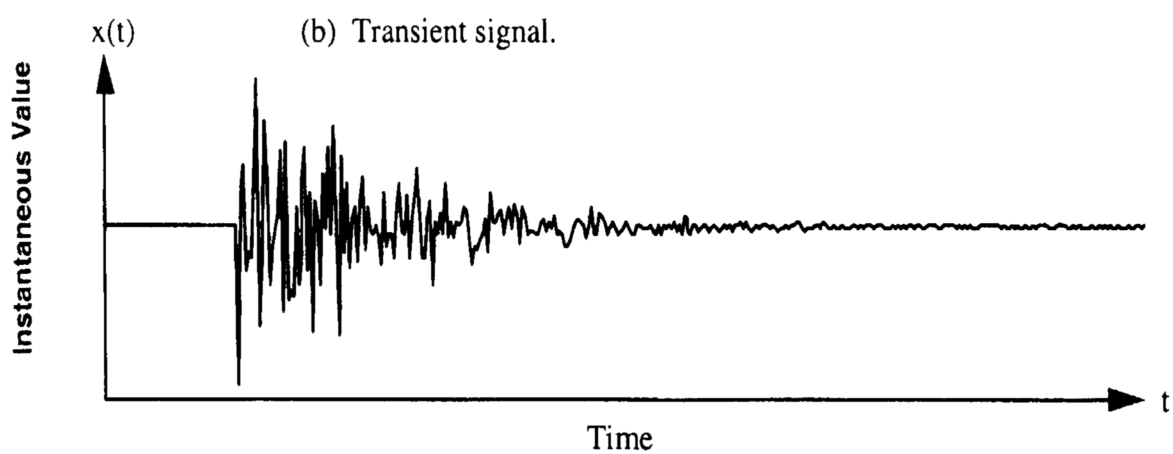
A signal can also be "time-invariant" or "time-varying," depending on whether the average properties of all time history signals representing the environment do or do not vary with time, at least over the time interval of interest.
Time-invariant random signals are usually referred to as "stationary" signals.



Structural Environments

TRANSIENTS

An environment is said to be transient if the signals representing the environment have a clear beginning and end, and a relatively short duration compared to the decay time of the impulse response function



Structural Environments

Environment (Section Number)	Mechanical Motion (M), or Pressure (P)	Sta. Random (R), Periodic (P), or Transient (T)	Upper Frequency Limit, Hz
Transportation	M	R, P, and/or T	50
Seismic loads	M	T	20
Wind and turbulence	P	R	20
Rocket motor ignition overpressure	P	T	40
Liftoff release	M	T	20
Engine/motor generated acoustic noise	P	R	10,000
Engine/motor generated vibration	M	R and P	2,000
Aerodynamic sources	P	R	10,000
Engine/motor thrust transients	M	T	100
Maneuvers during ascent	M	T	10
Pogo	M and P	P	125
Solid motor pressure oscillations	P	P	1,000
Liquid sloshing in tanks	M and P	R	5
Stage and fairing separations	M	T	50
Pyrotechnic events	M and P	T	100,000
Flight operations	M	T	10
Onboard equipment operations	M	R, P, and/or T	10,000
Planetary descent, entry, and landing loads	M and P	R and/or T	10,000
Surface penetration	M	T	3,000
Meteoroid impacts	M	T	-

Structural Environments

- Normal Tolerance Limits (NTL)
  - There are several procedures for selecting limit loads.
  - At the Observatory (SC) level it is usual to get limit loads in terms of NTL.
  - A NTL is derived at each frequency bandwidth.
  - There is evidence that structural response spectral values fits lognormal distribution.
    - **$y = \log_{10} x$**
    - **$NTLy(n, \beta, \gamma) = y_{mean} + k_{n, \beta, \gamma}\, Sy$**
      - **Where:**
        - » **n=# predictions**
        - » **y mean=mean**
        - » **Sy = standard deviation of y**
        - » **$k_{n, \beta, \gamma}$= normal tolerance factor**

Structural Environments

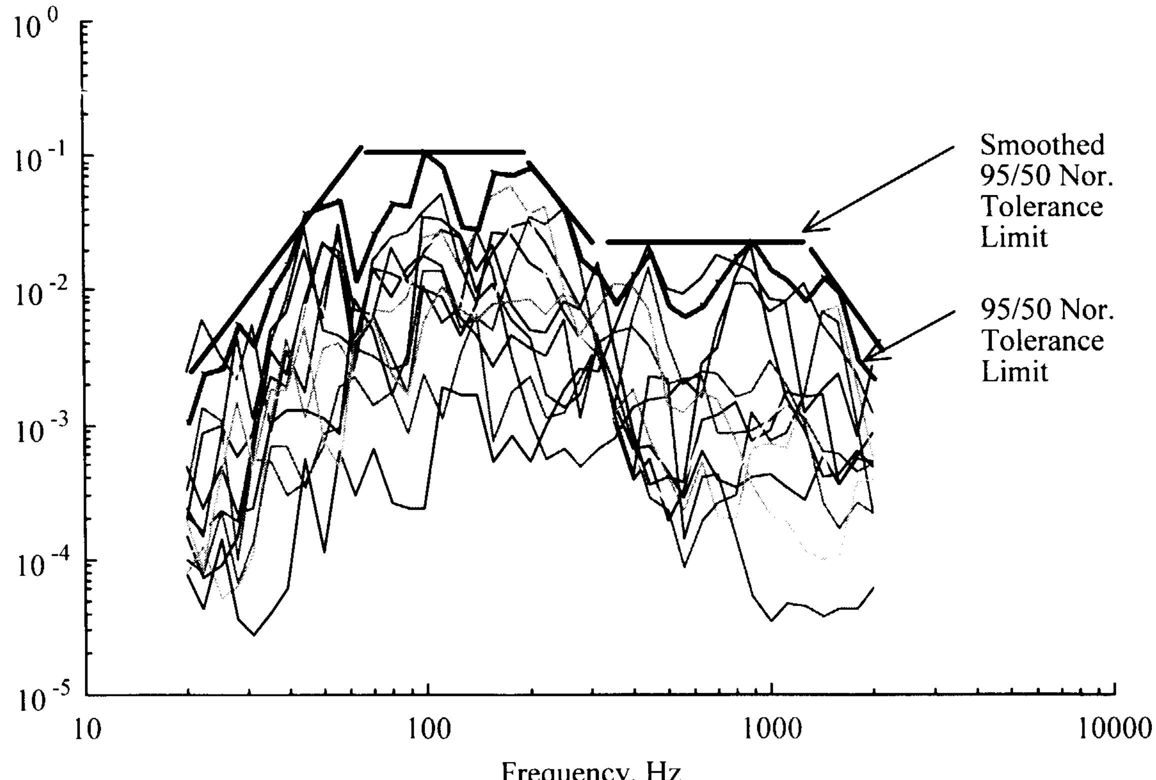
- Example
  - For **β=0.95, γ=0.5 and n=10**
  - 95/50 limit = 95 % normal tolerance limit with 50 % confidence
  - Interpreted as= limit that will exceed the response spectral values for at least 95% of all points within the zone with a confidence of 50%.
  - $\mathbf{k}_{\mathbf{n},\,\boldsymbol{\beta},\,\boldsymbol{\gamma}=1.7}$

Normal Tolerance Limit				10
predict#	logvalue	mean	std dev	95/50
1	3	4.900	1.663	7.728
2	5			
3	4			
4	2			
5	6			
6	7			
7	7			
8	5			
9	6			
10	4			

n	$\gamma = 0.50$			$\gamma = 0.75$			$\gamma = 0.90$		
	$\beta=0.90$	$\beta=0.95$	$\beta=0.99$	$\beta=0.90$	$\beta=0.95$	$\beta=0.99$	$\beta=0.90$	$\beta=0.95$	$\beta=0.99$
3	1.50	1.94	2.76	2.50	3.15	4.40	4.26	5.31	7.34
4	1.42	1.83	2.60	2.13	2.68	3.73	3.19	3.96	5.44
5	1.38	1.78	2.53	1.96	2.46	3.42	2.74	3.40	4.67
6	1.36	1.75	2.48	1.86	2.34	3.24	2.49	3.09	4.24
7	1.35	1.73	2.46	1.79	2.25	3.13	2.33	2.89	3.97
8	1.34	1.72	2.44	1.74	2.19	3.04	2.22	2.76	3.78
9	1.33	1.71	2.42	1.70	2.14	2.98	2.13	2.65	3.64
10	1.32	1.70	2.41	1.67	2.10	2.93	2.06	2.57	3.53
12	1.32	1.69	2.40	1.62	2.05	2.85	1.97	2.45	3.37
14	1.31	1.68	2.39	1.59	2.01	2.80	1.90	2.36	3.26
16	1.31	1.68	2.38	1.57	1.98	2.76	1.84	2.30	3.17
18	1.30	1.67	2.37	1.54	1.95	2.72	1.80	2.25	3.11
20	1.30	1.67	2.37	1.53	1.93	2.70	1.76	2.21	3.05
25	1.30	1.67	2.36	1.50	1.90	2.65	1.70	2.13	2.95
30	1.29	1.66	2.35	1.48	1.87	2.61	1.66	2.08	2.88
35	1.29	1.66	2.35	1.46	1.85	2.59	1.62	2.04	2.83
40	1.29	1.66	2.35	1.44	1.83	2.57	1.60	2.01	2.79
50	1.29	1.65	2.34	1.43	1.81	2.54	1.56	1.96	2.74
∞	1.28	1.64	2.33	1.28	1.64	2.33	1.28	1.64	2.33

Structural Environments

- NTL are usually smoothed by enveloping with a series of straight lines as per figure



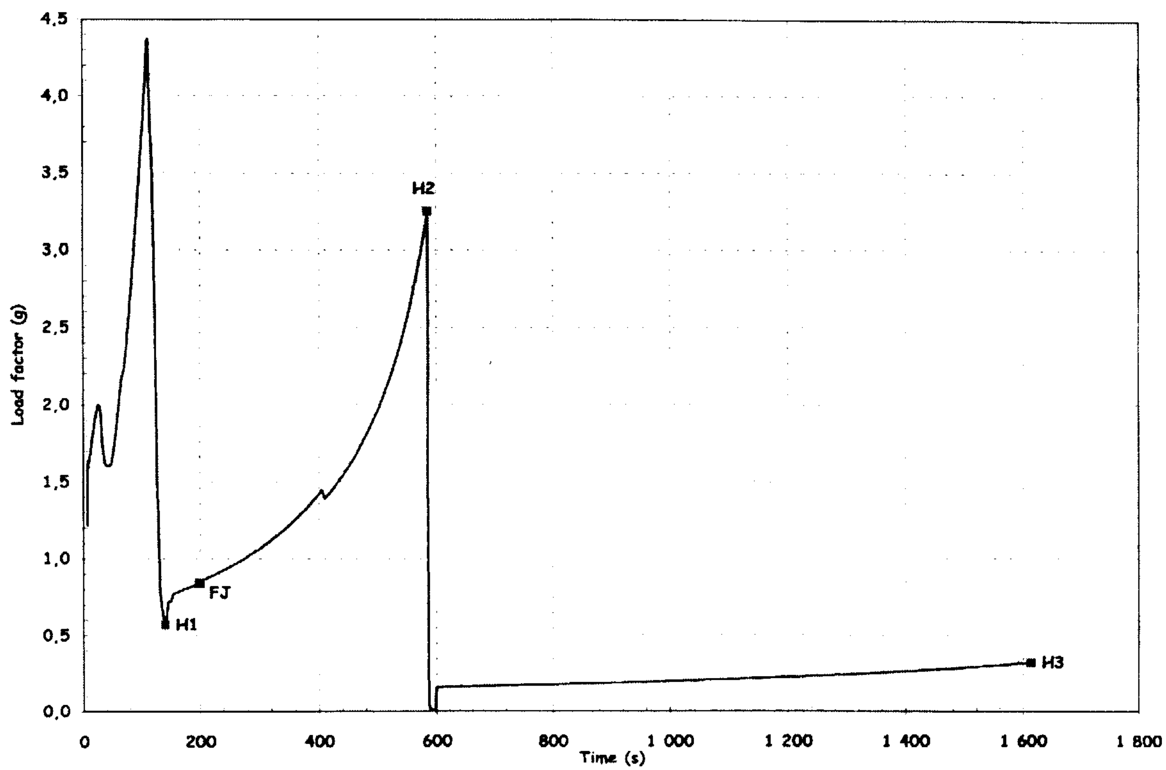
- There are a separate set of FS and loads for design and test of Ground Support Equipment (GSE)

Structural Environments

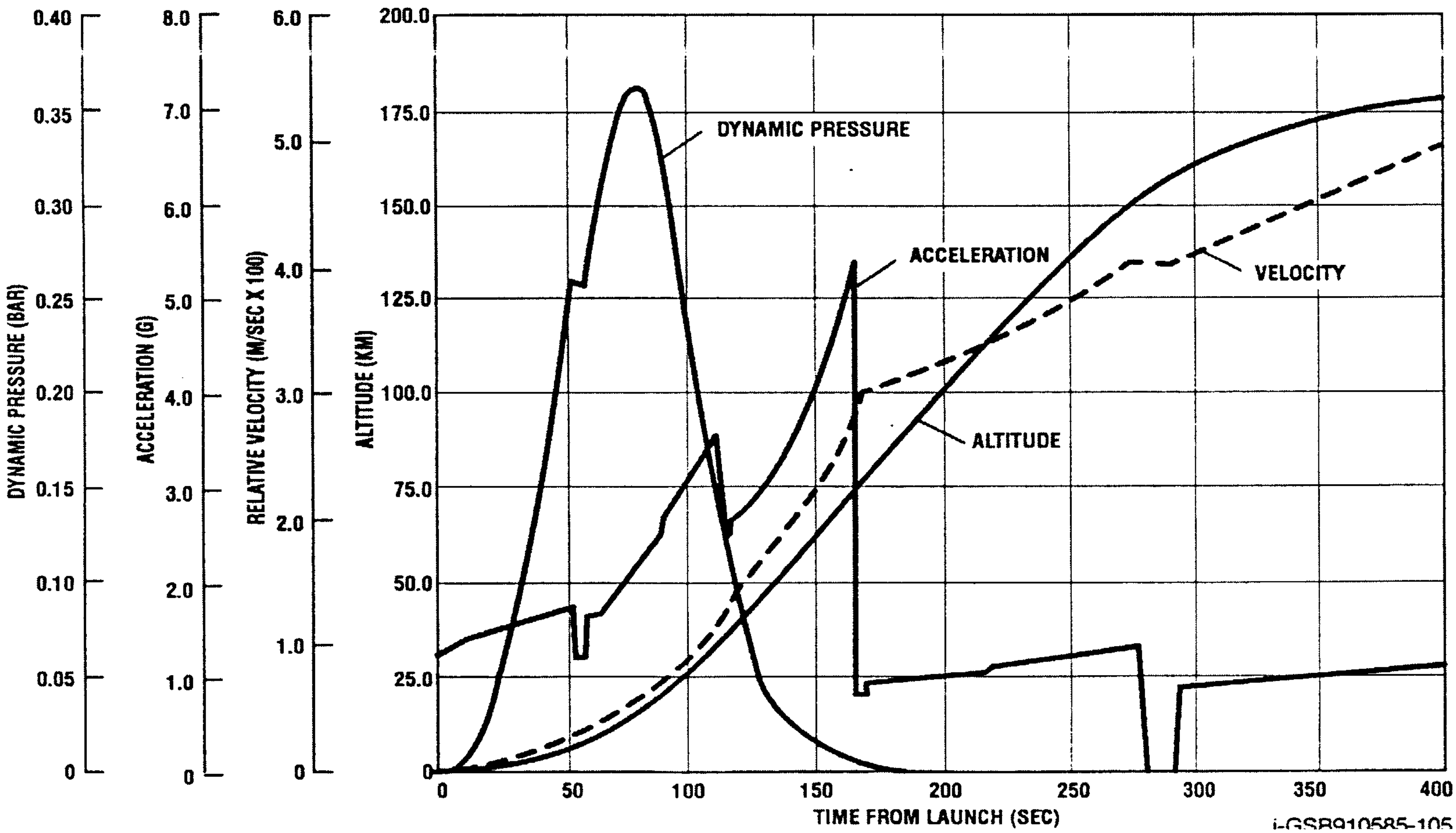
- Typical Launch Environment
  - Typical flight profile and associated environment

Structural Environments

- Longitudinal static accelerations (mention to lateral)



Structural Environments



Structural Environments

–QSL factors (flight limit loads to be used at SC level design/test)

- Combination of steady-state acceleration due to the engine thrust, and slowly variable acceleration due to dynamic effects of a transitory nature (e.g., engine thrust termination, buffeting, gust, etc.).

- Peak steady-state acceleration is reached at burn-out (lowest mass):

  –Depends on launch vehicle configuration, launch profile, and S/C mass.

Structural Environments

Flight event \ Acceleration (g)	Longitudinal		Lateral
	Static	Dynamic	Static + Dynamic
Lift-off	- 1.7	± 1.5	± 1.5
Maximum Dynamic Pressure	- 2.7	± 0.5	± 2
P 230 Thrust oscillations	- 4.25	± 1.75	± 1
H155 thrust tail-off	- 0.2	± 1.4	± 0.25

Structural Environments

- Dynamic loads depend on the dynamic coupling of the L/V and S/C natural vibration modes.
  - Dynamic coupling is reduced by separating S/C fundamental natural frequencies from L/V natural frequencies.

- Applies uniformly over the structure complying with S/C CG constrains and minimum frequency requirements defined by L/V user's manuals.

- SC primary structure is in general designed to the QSL (if frequency and CG requirements are met).

- SC secondary structures are designed to dynamic loads, taking into account the spacecraft structural amplifications.

Structural Environments

- Typically Coupled Loads Analyses (CLA) are performed by the LV manufacturer at several phases of the program in order to generate loads for low frequency SC and components environments and also to check for fairing envelope clearances.

- Events such as lift-off, transonic, boosters separation etc are analyzed. Updates on the QSL are obtained as well as dynamic loads.

- The final CLA allow to condition or to check the qualification or acceptance tests of the payloads.

- Some events are more sinusoidal like, while others are just transients, in any case shock response spectra is used to generate mission specific equivalent sine inputs floors at the base of the SC.

Structural Environments

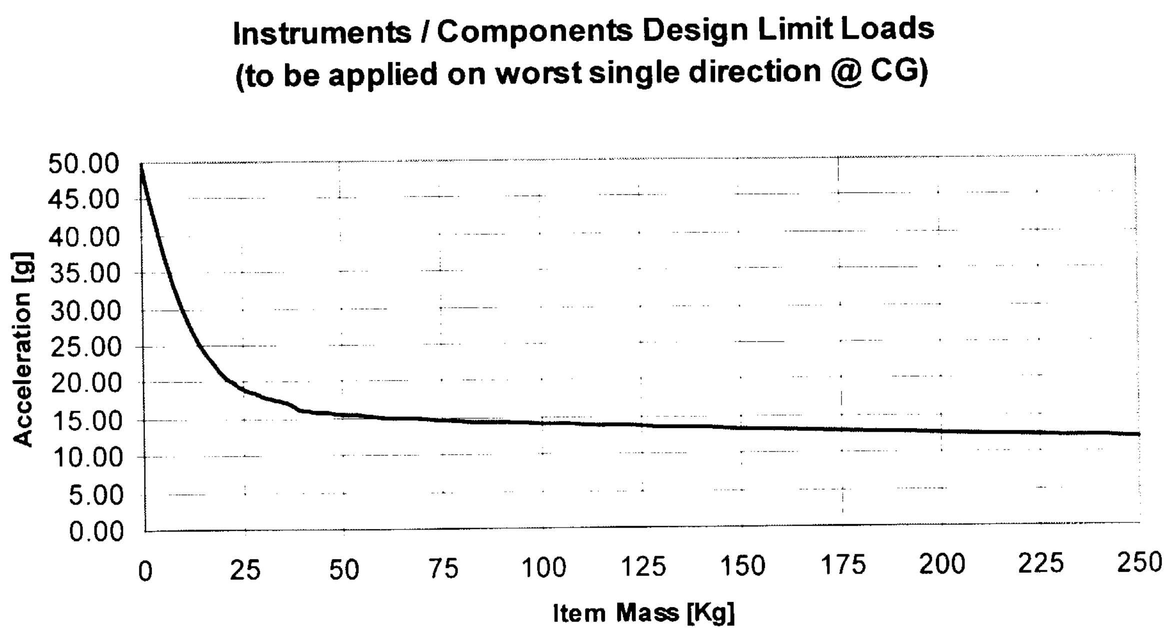
- Generic Sinusoidal Input requirements are presented as follows

	Frequency range (Hz)	Qualification levels (0-peak) (recommended)	Acceptance levels (0-peak)
Longitudinal	4 - 5 5 - 100	12.4 mm 1.25 g	9.9 mm 1 g
Lateral	2 - 5 5 - 25 25 - 100	9.9 mm 1 g 0.8 g	8.0 mm 0.8 g 0.6 g
Sweep rate		2 oct./min	4 oct./min

A notching procedure can be agreed on the basis of dynamic coupled load analysis results and after a low level run.

Structural Environments

- At the instrument / subsystem / component level QS preliminary load factors are sometimes based on mass acceleration curves.



Structural Environments

- Vibro-acoustics environments

    - Typically random vibration at the base of the SC and Acoustic loads are available from the LV users guide and later on might be adjusted to mission specific

    - For small SC (<1000 lb) and LV's (Pegasus/Taurus), random vibration loads are used for design and test of the SC. For greater SC and LV's loads generation is based on acoustics.

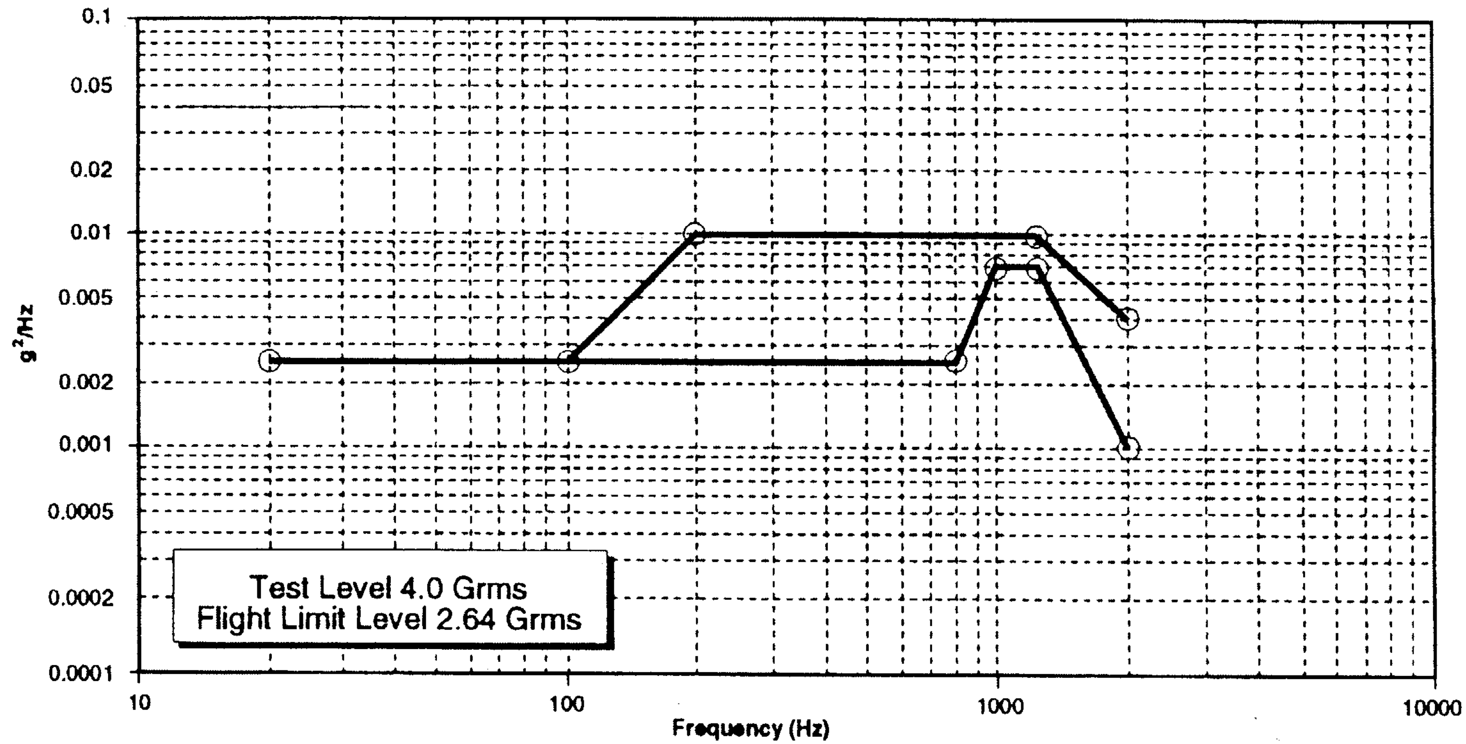
Structural Environments

Random Vibration:

- Random vibrations are generated by functioning mechanical elements (e.g. turbopumps), combustion phenomena or structural elements excited by the acoustic environment. Such vibrations are specified at the base of the SC.
- Random vibrations has frequency content at all frequencies (20 - 2000Hz) and varying peak amplitudes at any instant of time.
- A Gaussian distribution is usually assumed for treatment.

Structural Environments

- A typical SC specification is presented in table (Pegasus)



Structural Environments

- Random specifications for components are derived from the next level of integration analysis or heritage, those levels should be at least equal to the minimum workmanship for components.

- Workmanship levels vary according to different standards. At NASA GSFC the levels to be used for workmanship follow the NASA GEVS recommendation.

- When analysis or heritage are insufficient to define a limit level, GEVS provides for a preliminary acceptance level.

Structural Environments

Vibration Test Levels Acceptance Components	
Frequency	Acceleration Spectral Density (G^2/Hz)
20	0.013
20 - 50	+6 dB/oct
50 - 800	0.08
800 - 2000	-6 dB/oct
2000	0.013
Overall	10.0 G_{rms}

The acceleration spectral density (ASD) level may be reduced for components weighing more than 22.7 Kg (50 lb) according to:

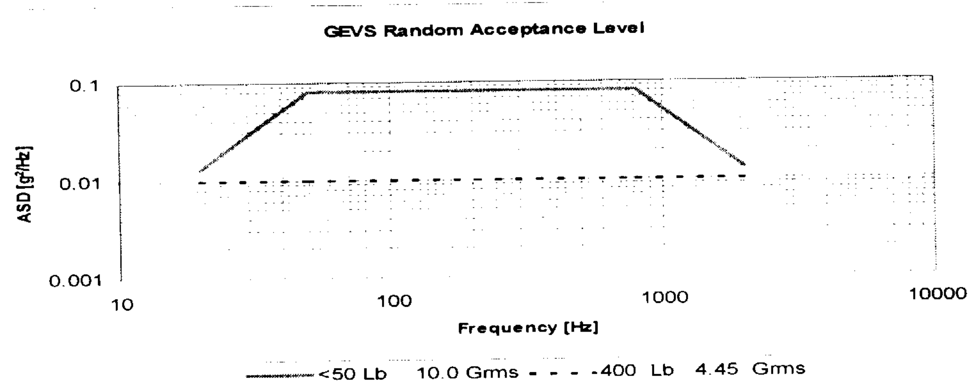
dB reduction = 10 LOG(W/22.7) or 10 LOG(W/50)

$ASD_{(50\ to\ 800Hz)}$ = 0.08 x (22.7/W) or 0.08 x (50/W)

where W = component weight in Kg or Lb

The slope shall be maintained at $\pm$ 6 dB/Oct for components weighing up to 59 kg (130 lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 G^2/Hz at 20 and 2000 Hz.

For components weighing over 182 Kg (400 lb), the test specification shall be maintained at the level for 200 Kg



Structural Environments

Components Minimum Workmanship Random Vibration Levels	
Frequency	Acceleration Spectral Density (G^2/Hz)
20	0.01
20 - 80	+3 dB/oct
80 - 500	0.04
500 - 2000	-3 dB/oct
2000	0.01
Overall	6.8 Grms

The plateau acceleration spectral density (ASD) level may be reduced for components weighing between 45.4 Kg (100 lb) and 182 Kg (400 lb) according to the component weight (W) up to a maximum of 6 dB as follows:

dB reduction = 10 LOG(W/45.4) or 10 LOG(W/100

ASD(plateau) level = 0.04 x (45.4/W) or 0.04 x (100

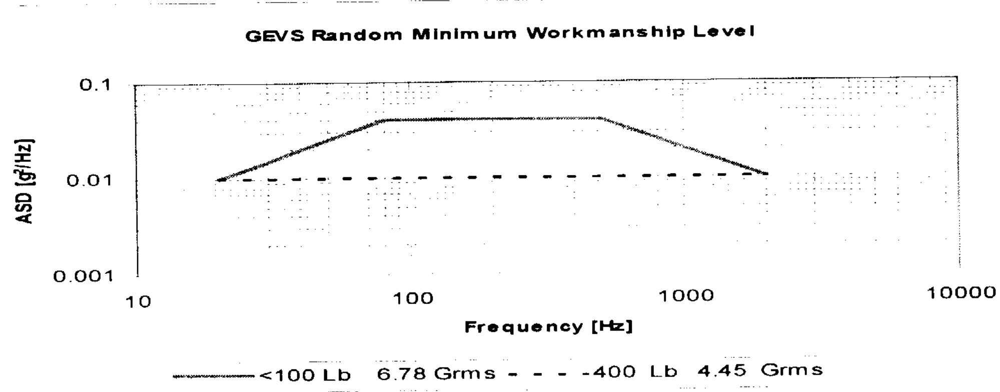
where W = component weight in Kg or Lb

The sloped portions of the spectrum shall be maintained at plus and minus 3 dB/oct. Therefore, the lower and upper break points, or frequencies at the ends of the plateau become:

F_L = 80 (45.4/W) or 80 (100/W) — F_L = frequency break point low end of plateau

F_H = 500 (W/45.4) or 500 (W/100) — F_H = frequency break point high end of plateau

The test spectrum shall not go below 0.01 G^2/Hz. For components whose weight is greater than 200 Kg, the workmanship test spectrum is 0.01 G^2/Hz from 20 to 2000 Hz with an overall level of 4.4 G_{rms}.



Structural Environments

- Area under the psd curve is the mean square response (MSR)
- RMS = (MSR)^.5
- Expected peak = n RMS
- Usually a 3 RMS value is assumed (3 sigma) for design.

Structural Environments

Interpretation:

0 - 1s values occur	68.31%	of the time
1s - 2s values occur	27.10%	of the time
2s - 3s values occur	4.33%	of the time
	99.74%	CHECK #

i.e.: 0.26% probability of exceeding a 3 value (for 'white noise' input)

Structural Environments

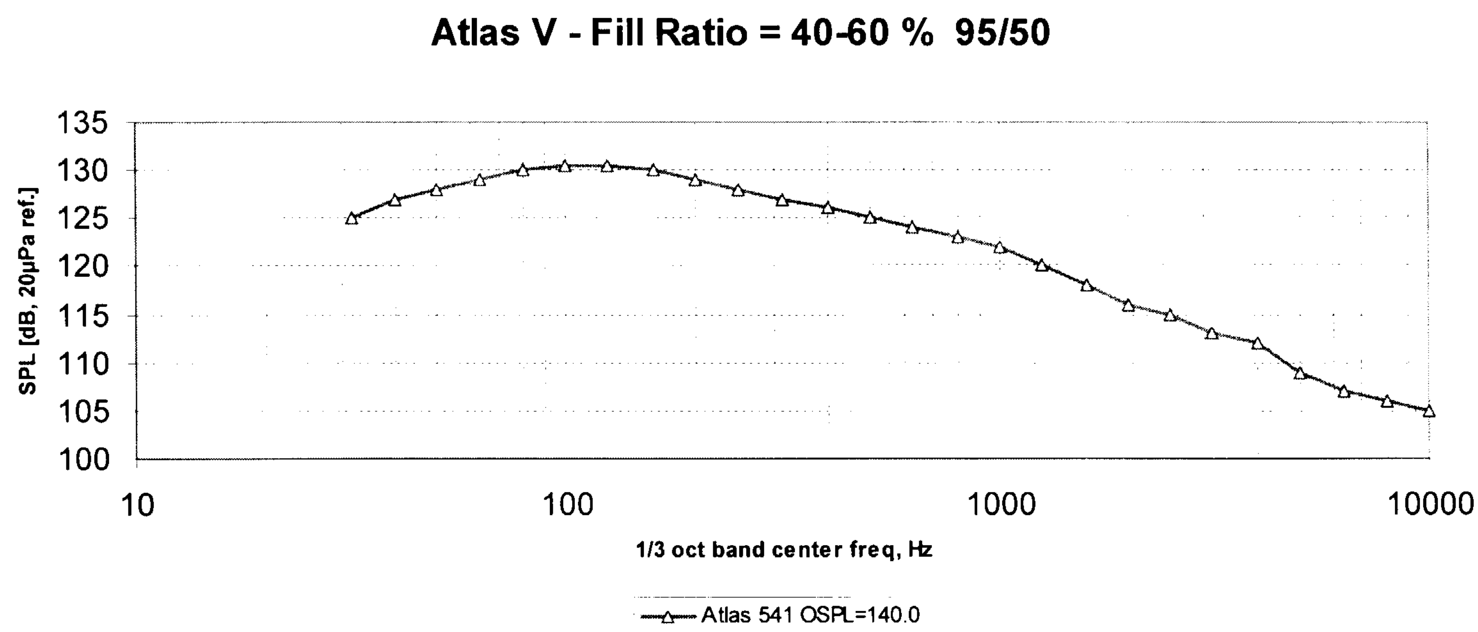
- Acoustics:

  - Acoustic vibrations are generated by engine noise, buffeting and boundary layer noise. The level is the highest at lift-off and in the transonic region. It is substantially lower outside of these periods.

  - A typical SC acoustic specification is presented in the next figure (Atlas V, flight expected). A fill ratio is usually defined.

    - Fill factor = SPL [dB] SC exterior – SPL [dB] inside empty fairing.

Structural Environments



Structural Environments

- The specification are based on field measurements using microphones or extrapolations techniques. Usually a fill factor is defined.
- Mics measuring pressure p
- P ref = 2.0 E-4 dyne/cm2 [Pa]
- Sound pressure level (SPL) is then expressed in dB = 20 log (p/p ref)
- Frequency spacing for each SPL value is usually 1/3 octave or 1 octave
- Overall SPL in also computed and specified.

Structural Environments

- The following table presents 1/3 octave center frequencies and their low (f_L) and high (f_H) ends.

- MSR [Pa^2] = $p\ ref^2\ 10^{(SPL/10)}$

- P rms [Pa] = (MSR)^.5

- P psd = p rms / (f_H-f_L)

1/3 oct	LOW	HIGH
32	28	35
40	35	45
50	45	56
63	56	71
79	71	89
100	89	112
125	111	140
160	143	180
200	178	224
250	223	281
315	281	354
400	356	449
500	445	561
630	561	707
800	713	898
1000	891	1122
1250	1114	1403
1600	1425	1796
2000	1782	2245
2500	2227	2806
3150	2806	3536
4000	3564	4490
5000	4454	5612
6300	5613	7072
8000	7127	8980
10000	8909	11225

Structural Environments

- Fill factors (FF) are usually positive (levels seen by SC > empty), and heavily dependent on the clearance between SC and fairing (fill factor increases with decreasing clearance and frequency)

- For example if the SC fills 80 % of the volume inside its fairing, and the clearance is 0.1 m.

    - FF(50 Hz) [dB] = 6.5
    - FF(250 hz) [dB] = 5.1

    - Usually levels are already accounting for a typical SC % volume

Structural Environments

- Pyroshock

- These are transient events induced by the activation of pyrotechnic devices incorporated into the attached structure. In certain cases the loading may be accompanied by the release of stored energy due to structural preload.

- Shock environments are usually defined by acceleration time histories. Often those are not very useful directly for shock analysis. Reduction to a different form is necessary, the type of reduction employed depends upon the ultimate use of the data. A typical reduction is a frequency domain fourier or shock response spectra (SRS)

Structural Environments

- Pyroshock rarely damages structural members,hence it is not considered a structural design driver.

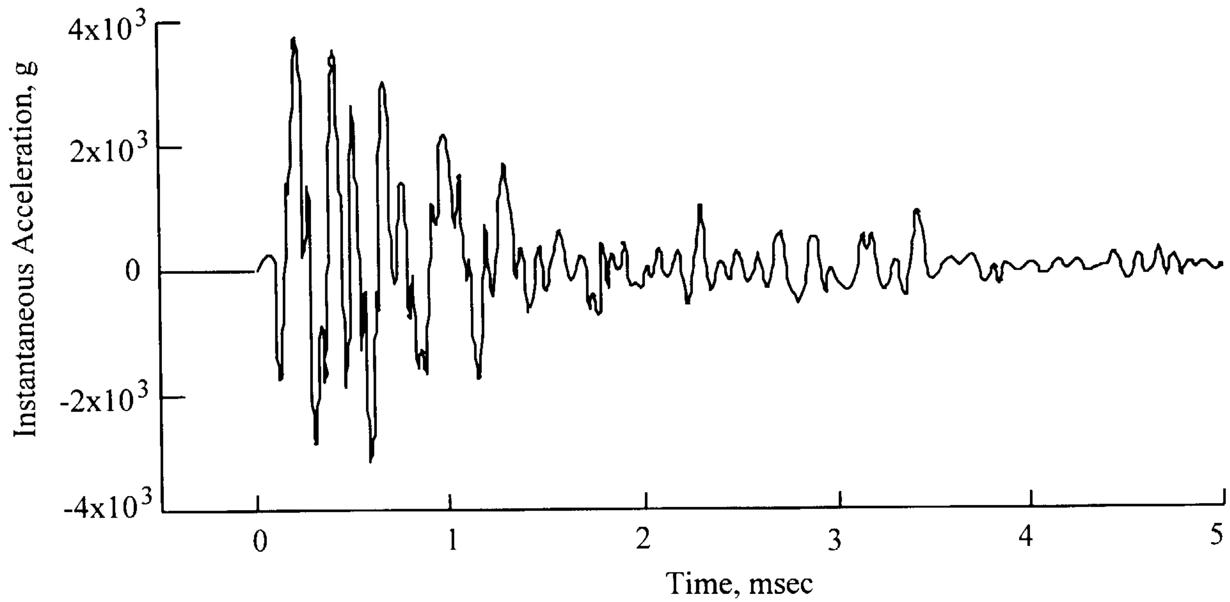
- Shock can easily damage “shock sensitive components”

  - Relay chatter
  - Separation of small circuit test items
  - Dislodging of contaminants (solder balls) which cause short circuits
  - Cristals,Glass, Optics
  - Sensors

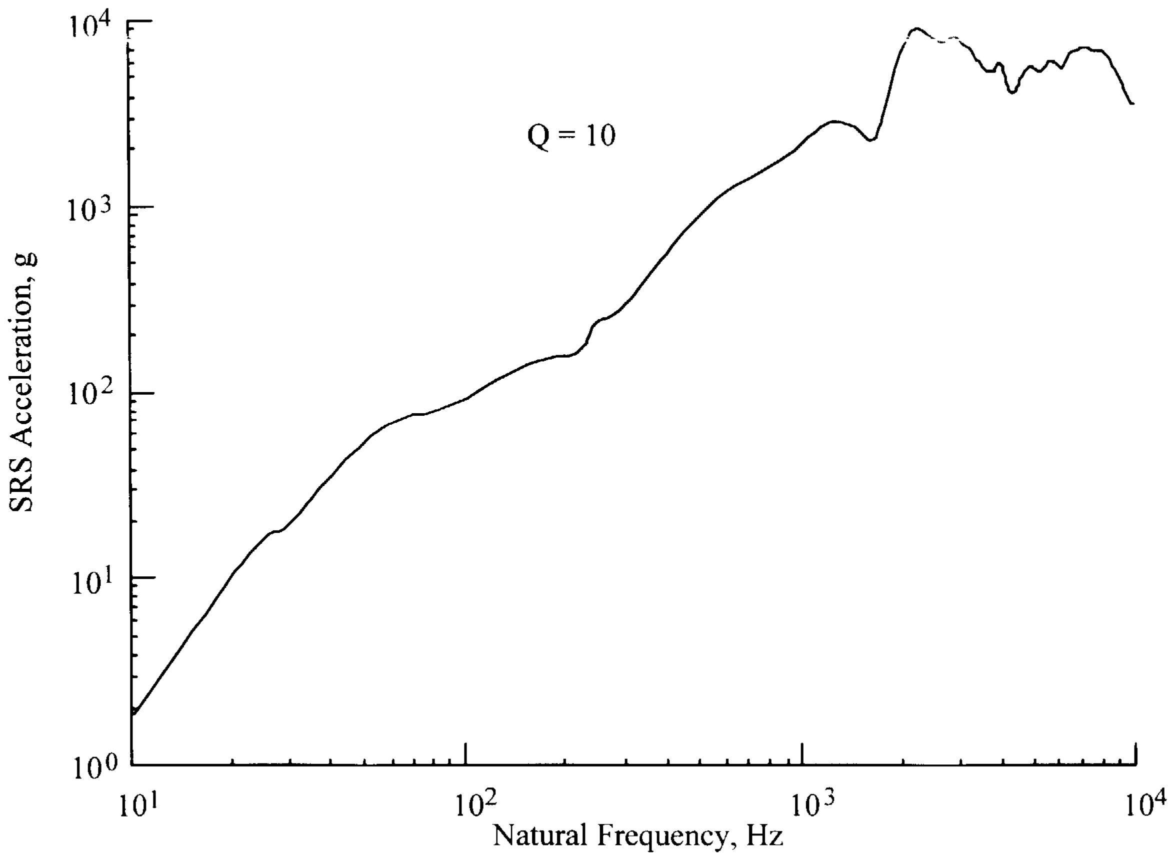
Structural Environments

- Usually 3 types of pyroshock categories are distinguished:
  - Near field = Direct wave propagation from source causing peak accelerations (TH) in excess of 5000 g and substantial spectral content above 100 kHz. No shock sensitive equipment should be located there. Depending on the severity of the source = 1 to 6 inches from it.
  - Mid field = combination of wave propagation and structural resonances, causing peak accelerations in the 1000-5000 g and substantial spectral content above 10 kHz. Distance ranges up to 1 ft away
  - Far field = Dominated by structural resonances, with peak accelerations below 1000 Hz and most spectral content below 10 kHz. Distances outside the mid range.

Structural Environments

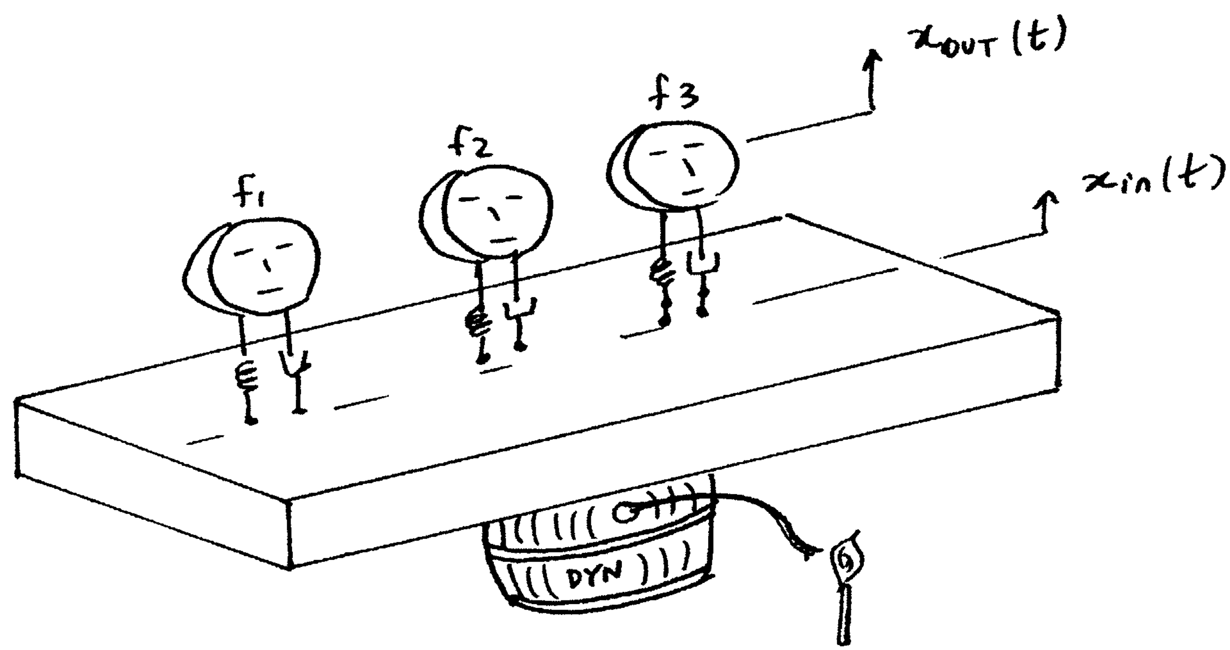


Structural Environments

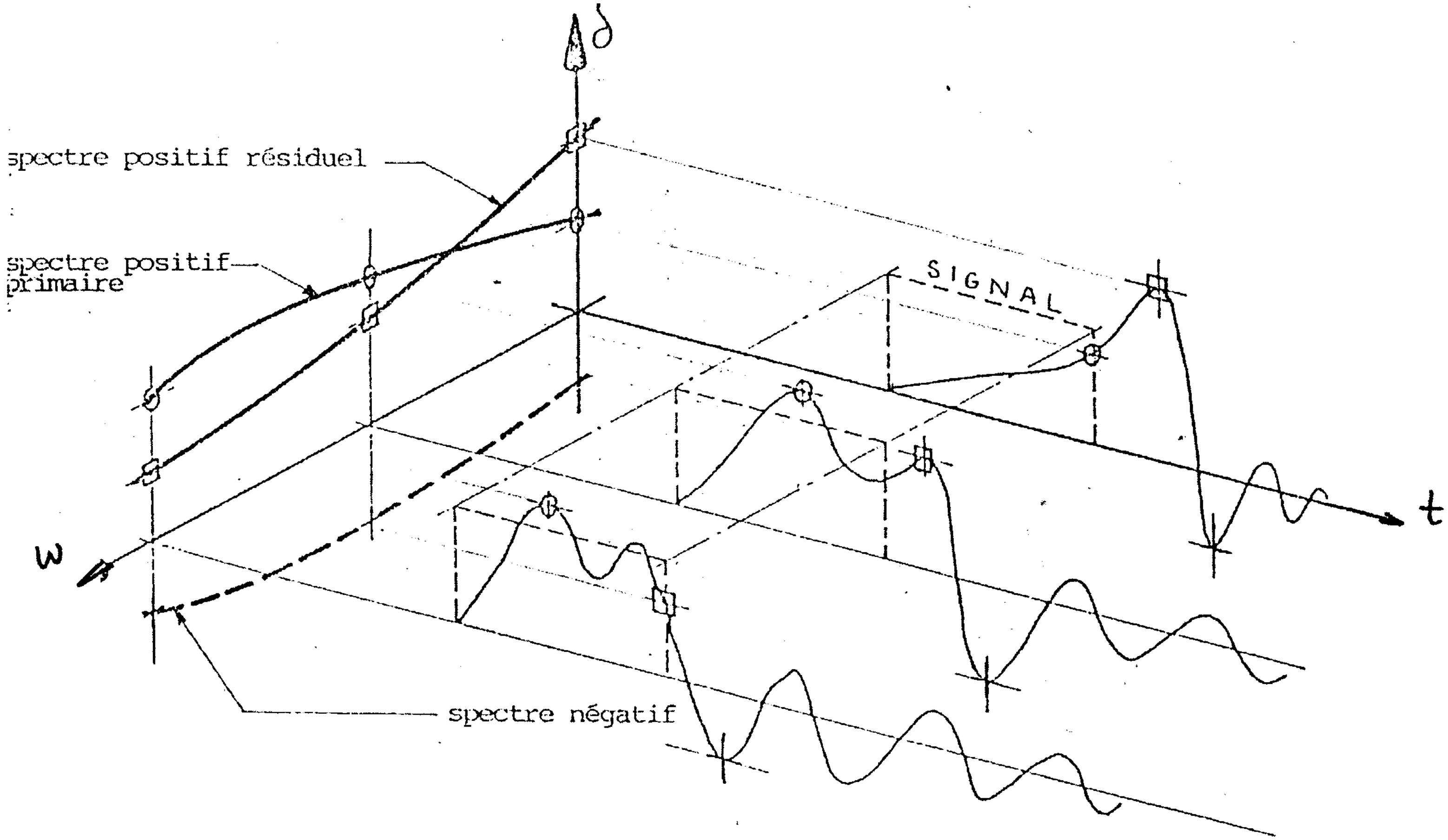


Structural Environments

- Shock Response Spectra



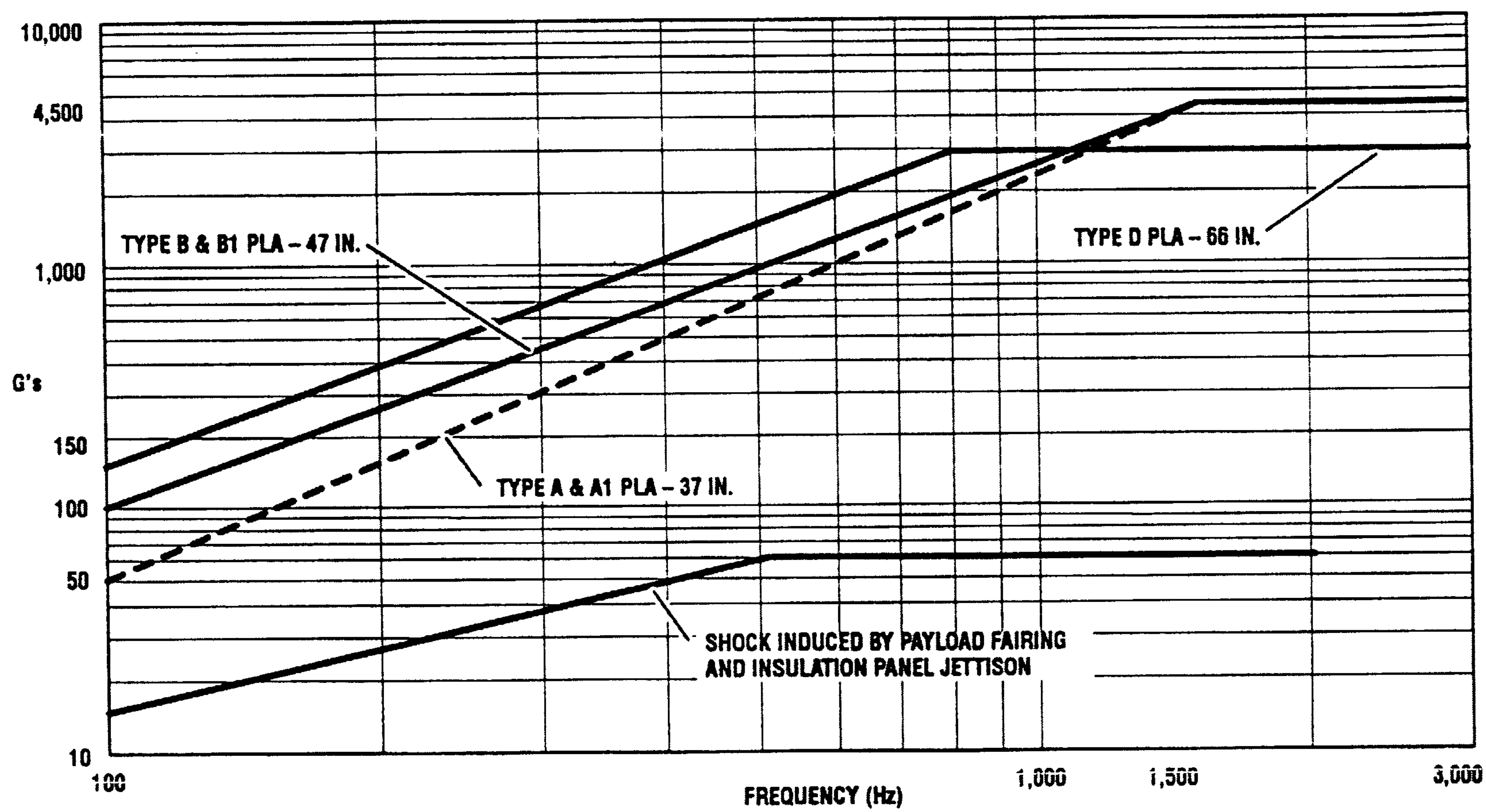
Structural Environments



Structural Environments

- Comments
  - If the peak occurs during application time, then it is called Primary SRS
  - If the peak occurs after, Residual SRS
  - Considering the full response time, Absolute SRS
  - Low frequency portion close to 6 dB/oct slope = constant velocity slope
  - A value of 50 in/sec is traditionally accepted as a low risk for equipment that does not have shock sensitive components
  - Damage potential proportional to velocity changes rather than acceleration

Structural Environments



Test Definitions

- TYPICAL HARDWARE HIERARCHY

  - PART
  - A single piece, or two or more joined pieces, which are not subject to disassembly without destruction or impairment of the design use, e.g., an integrated circuit or a roller bearing.

  - SUBASSEMBLY
  - The term subassembly denotes two or more parts joined together to form a stockable unit which is capable of disassembly or part replacement. Examples are a printed circuit board with parts mounted, or a gear train.

Test Definitions

•ASSEMBLY

•An assembly is the lowest level of "line replaceable unit" in the subsystem/system configuration. An assembly is a functional unit that is viewed as an entity for purposes of analysis, manufacturing, testing, maintenance, and record keeping. Examples are valves, electrical harnesses, individual electronic boxes such as transmitters, receivers or multiplexers, science instrument integrated optics, shutters, filter wheels, and focal plane detector arrays .

•COMPONENT

–A component is a functional unit that is viewed as an entity for purposes of analysis, manufacturing, maintenance, or record keeping. Examples are hydraulic actuators, valves, batteries, electrical harnesses, and individual electronic boxes such as transmitters, receivers, or multiplexers.

•

Test Definitions

- SUBSYSTEM
  - A subsystem is an assembly of two or more components including the supporting structure to which they are mounted, and any interconnecting cables or tubing. A subsystem is composed of functionally related components that perform one or more prescribed functions. Typical space vehicle subsystems are electrical power, attitude control, telemetry, instrumentation, command, structure, thermal control, and propulsion.

- SYSTEM
  - A system is the composite of equipment, skills, and techniques capable of performing or supporting an operational role. A system includes all operational equipment, related facilities, material, software, services, and personnel required for its operation. Examples of systems that include space vehicles as a major subtier element are launch systems and on-orbit systems.

Test Definitions

•VERIFICATION

• Verification provides objective evidence through test and/or analysis that specified design and workmanship requirements have been fulfilled

ACCEPTANCE TESTS

• Acceptance tests are conducted to demonstrate acceptability of an item for delivery. They are intended to demonstrate performance to specification requirements and to act as quality control screens to detect deficiencies of workmanship, material, and quality.

•DEVELOPMENT TESTS

• Development tests include all tests conducted to obtain information to aid in the design and manufacturing processes. Development tests are conducted to generate design parameters, validate design concepts, verify design criteria, determine design margins, identify failure modes, and to verify manufacturing processes. Development testing may be informal in that controlled design and test documentation, formal certification, formal retest requirements, and flight type hardware are usually not required.

Test Definitions

- PROTOFLIGHT TESTS
- A protoflight test is applied to one-of-a-kind flight hardware to meet the goals of both qualification and acceptance testing. For space vehicle hardware, the criteria for such tests are commonly the same as for a qualification test, except the test level and/or duration are reduced to minimize possible wearout damage to the hardware.

- QUALIFICATION TESTS
- Performed on test-dedicated flight-quality hardware at levels with conservative margins over worst case predicted flight environments. Test verifies that the flight equipment design is adequate to perform as required throughout the ground and mission environment exposures

Verification Phylosophies

VERIFICATION

Verification is the process of demonstrating that a specific hardware configuration meets the intended "design" and "performance" requirements and is certified for flight. Hardware are verified by successfully passing a proto-flight or acceptance test program. Proto-flight testing is required of all flight units that cannot demonstrate qualification heritage. Acceptance testing may be performed on follow-on units of designs that have been previously qualified. Hardware verification is intended to demonstrate performance to specification requirements and to act as a quality control screen to detect deficiencies of workmanship, material, and quality of the flight units.

When testing is physically prohibitive due to hardware or resource limitations, and it is judged that there is negligible risk by not performing a test, analysis of hardware compatibility with the mission requirements is required to demonstrate the acceptability of hardware for flight. In addition some metal structural components can be verified by analysis using no test factors.

Verification Phylosophies

These days a usual verification approach will inlcude:

Observatory level Protoflight tests

Lower levels of assembly: verified by test using a Protoflight program (PF/PF approach) or a Qualification/ Flight Acceptance program (Qual/FA approach). Qual or PF testing shall be performed prior to FA testing of subsequent items.

Note: *In certain cases a Protoflight/Flight Acceptance test program (PF/FA approach) may be acceptable upon program approval. Testing all flight items to Protoflight levels (PF/PF approach) is the preferred approach for the purpose of enhanced reliability demonstration. A pre-requisite for the Qual/FA or PF/FA approach is that all units intended for flight must use the same class parts, be built to the same set of drawings, and use the same qualified materials and processes. PF tests may be required in lieu of FA tests if modifications are made to the flight hardware after the original design has been qualified.*

Design/Test Flow for Each Environment